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Einstein Telescope site selection: seismic and gravity gradient noise

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Abstract. Gravity gradient noise generated by seismic displacements may be the limiting factor for the sensitivity of third-generation gravitational wave detectors at frequencies below 10 Hz. A finite element framework has been developed to calculate the soil response to various excitations. The accompanying gravity gradients as a result of the seismic displacement field can then be evaluated. The results of the gravity gradient noise are in good agreement with previous analytical results. Finally results of gravity gradient noise from a single pulse excitation of a homogenous medium are discussed for an underground detector.

1. Introduction

At this moment the first generation of interferometric gravitational wave (GW) detectors have reached their design sensitivities and second generation detectors are poised to upgrade these sensitivities by a factor of 10 within the next decade. The Einstein Telescope (ET) design study [1] initiates research to explore possibilities beyond the second generation detectors. The third generation of detectors will improve sensitivities by a factor of 10 over a broad frequency spectrum.

A particular challenge will be to detect signals at frequencies below 10 Hz. It is expected that sensitivity at these frequencies will be limited by fluctuations in the local gravitational field as a result of fluctuating density variations in the surrounding soil. These field fluctuations couple directly to the interferometer test masses and are known as gravity gradient (or Newtonian) noise (GGN). A full understanding of seismic activity, seismic wave characteristics and how these affect GW detectors through gravity gradients is imperative to achieve the desired sensitivity. These studies have been the prime focus of working package 1 of the ET design effort in the past eighteen months.

Sources of seismic noise include earthquakes, atmospheric and oceanic disturbances, and cultural noise. The latter is a result of human activity such as footsteps, traffic and machinery. Analytical descriptions of seismic activity fall short when considering a non-homogeneous medium or complex geology and a time domain finite element (FE) framework to model seismic activity has been developed that allows to study the impact of GGN on GW detectors.

2. Studies of seismic noise

Noise studies differentiate noise sources according to frequency f and for Einstein Telescope the critical frequencies f are in the range 1 - 10 Hz, where the response is most variable mainly due to cultural noise. It is therefore important to choose a site location far from human activities both at present and in future. In Europe low noise sites are located in the center of the continent. For example in various locations in Germany displacement noise densities have been measured as low as 1 nm/rtHz at 1 Hz that approximately drop as $1/f^2$. For Einstein Telescope additional suppression of GGN (by a factor 10 – 100) is needed and it is imperative that an underground infrastructure is realized.

2.1 Seismic noise finite element modeling

As a result of seismic disturbances a displacement wave field is produced that is governed by the elasto-dynamic equations. Wave solutions include pressure (P) and shear (S) body waves, and Rayleigh and Love surface waves. Simulation of the ground displacement fields was done with a FE software package.

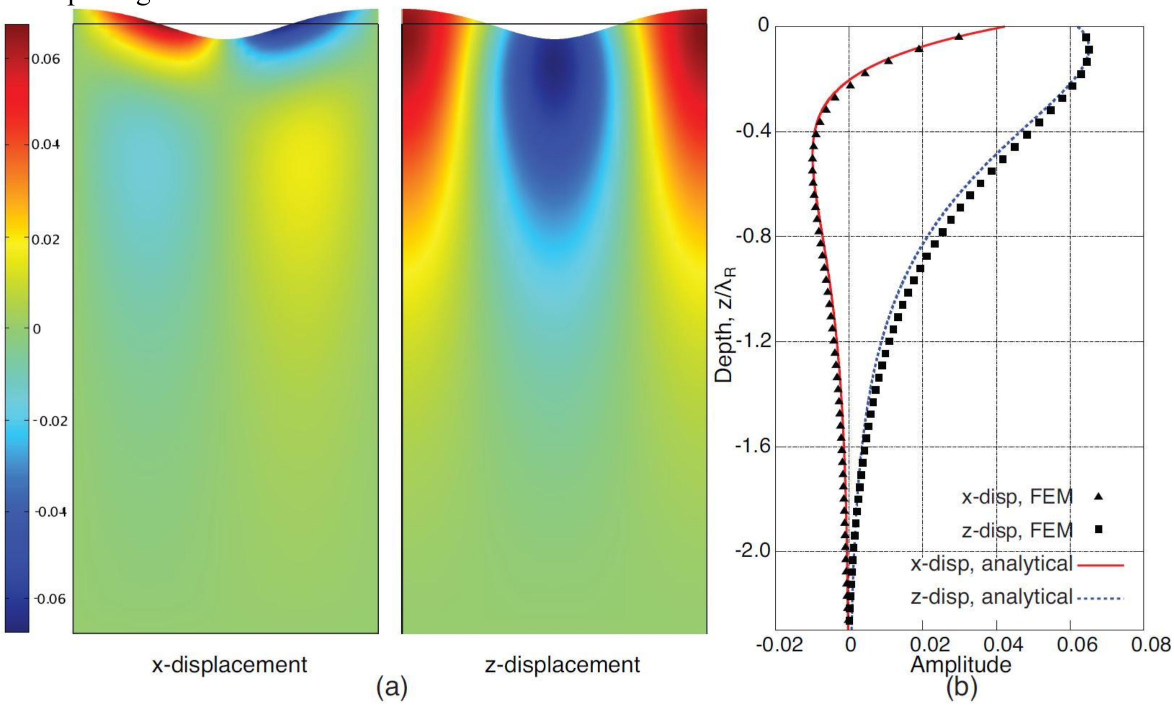

Figure 1. (a) Rayleigh wave displacement fields for a wave propagating in the x direction. (b) FE and analytical calculations of Rayleigh wave displacements (λ_R denotes the Rayleigh wavelength).

The ground motion response calculated by the FE model is in good agreement with analytical solutions for Rayleigh waves (see Fig.1). The x and z components attenuate differently with depth and the x component changes sign at a depth of about 0.2 λ_R.

3. Studies of gravity gradient noise

In our FE analysis the acceleration is given by the summation of the contributions $\mathbf{a}_i$ from each node i with mass m_i. When a seismic displacement field is present, the nodes suffer a displacement denoted by $\xi_i(\mathbf{r}, t)$. The gravity gradient acceleration due to these displacements is given by

$$\mathbf{a}^{NN}(\mathbf{y}, t) = \sum_i (\nabla \otimes \mathbf{a}_i)^T \xi_i(\mathbf{r}, t).$$

Note that in the gravity gradient calculations presented here, the mass associated with each node is assumed to be constant.

3.1 Finite element modeling of gravity gradient noise for a surface detector

The FE results are compared with the analytic results of Saulson [2] and Hughes and Thorne [3] for a surface detector. To facilitate comparison, an integral cut-off radius equal to that used in Saulson's analysis ($\lambda/4$) was employed in the summation process. Fig. 2 shows that good agreement is obtained. In the limit that the cut-off radius decreases to zero, GGN increases by about a factor 2.

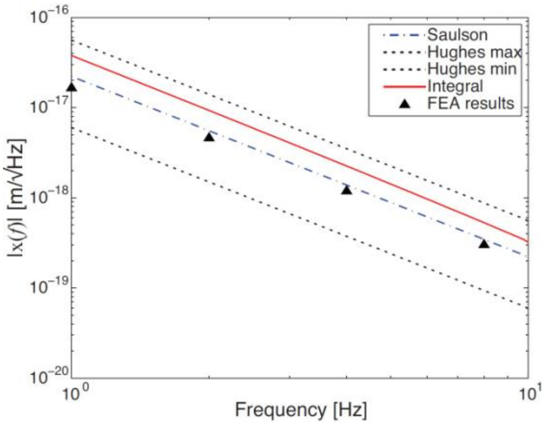

Figure 2. FE results of GGN displacement noise for a surface detector. For comparison the results of Saulson, Hughes and Thorne are shown (the red line represents the limit that the cut-off radius decreases to zero).

3.2 FE modeling of gravity gradient noise for an underground detector

Pulse excitations at the centre of a half-sphere model were used to investigate FE GGN modeling for an underground detector (see Fig. 3). The nodal displacements were recorded as a function of time and the GGN accelerations were calculated at various depths at 800 m from the z-axis.

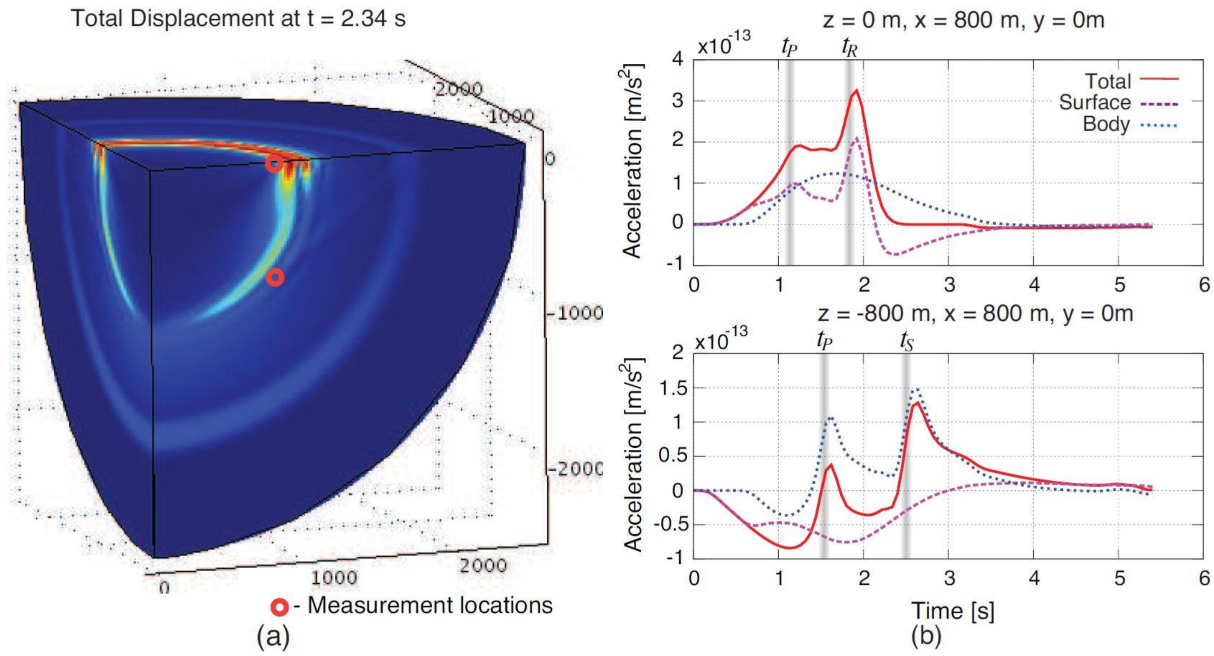

Figure 3. (a) Pulse excitation of a homogeneous half-sphere. (b) Time domain evolution of GGN acceleration (horizontal) at a surface (z=0 m) and underground (z=-800 m) test mass. Arrival times of Rayleigh, S and P-waves are also indicated.

The FE analysis indicates strong contributions from Rayleigh waves for a surface detector and body waves for a subterranean detector. This FE framework can be an effective tool in investigating gravity gradients for subterranean gravitational wave detectors. This allows further research into quantitative effects of seismic motion on GGN and implications of geology and infrastructure.

References

[1] Einstein Telescope design study (Grant Agreement 211743). See http://www.et-gw.eu/
[2] Saulson P 1984 Phys. Rev. **D** 30 732–736
[3] Hughes S and Thorne K 1998 Phys. Rev. **D** 58 122002